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SPACECRAFT RE-FLUIDING

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Abstract

The ever-increasing number of space assets and interplanetary missions is creating a requirement for spacecraft service on-orbit. A large demand for this servicing in space is the resupply of consumables and propellants. The benefits of refueling, or refluiding as it will be come to be called, are shown in this paper. A discussion of the issues involved with transporting fluids in zero-gravity is also included. Furthermore, the technology necessary to make spacecraft refluiding feasible is demonstrated. The main focus of the paper is on the implementation of a servicing vehicle. The propulsion performance necessary for both a manned and automated servicer is investigated using an existing system design that would be based at the International Space Station. The advantages and disadvantages of each system are discussed. The importance of a high performance propulsion system is shown and recommendations are made on this subject. Overall, the servicing vehicle is shown to be most efficient if it were automated and able to provide many services.

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INTRODUCTION

The space age has given people orbiting assets that can provide global communication, global positioning, unprecedented information gathering capabilities and many other technologies that enhance the way we live. Currently, satellites and spacecraft are designed for a certain life span based either on demand for the service the system provides, or for physical limitations such as fuel or power. The amount of fuel also limits satellite maneuvering, and if the fuel is used up during a position change, the spacecraft's life is shorted. Manned exploration missions require large amounts of fuel for their travels through space. Satellite refluiding is a developing technology that could have a positive impact on spacecraft versatility, performance, and lifespan.

Throughout this paper you will continue to read the word "refluiding". I found it necessary to use the word refluiding because it more accurately describes the process of transporting not only fuels, but also any other liquids, between orbiting craft.

Although there are many aspects of satellite refluiding that could be explored, my research has thrust me in a certain direction. When I initially began questioning professors and colleagues about refueling satellites on-orbit, many were fascinated by the idea, but some simply asked me "why would you want to do that?". This led to an investigation of the reasons for satellite refluiding. Once I understood why refluiding could be beneficial, the next questions that I heard were "Can you transfer fluid between spacecraft?" and "What method are you going to use to get the spacecraft refueled?". It then seemed necessary to answer such questions to proceed in the manner of "not putting the cart before the horse". Therefore, I will focus on the following basic issues:

1. The need for satellite refluiding
2. Demonstrating that On-Orbit refluiding can be accomplished
3. Methods for and Analysis of Satellite Refluiding
4. Conclusion and Recommendation for Further Study

By focusing on these key points, a strong foundation in the area of refluiding can be established. I found it extremely important to investigate the propulsion performance necessary to rendezvous with, and return from, the position where fluid resupply is needed. After all, if you can't get to the satellite, you can't service it!

During the course of this paper, I will continue to make references to a quantity called ΔV. I will provide a BRIEF description of what this means, but a more complete understanding would be desirable for the reader. Basically, the spacecraft must accomplish a specific amount of ΔV anytime it needs to change position (initial launch, change in altitude or inclination, etc.). The larger the amount of ΔV, the more fuel is necessary to complete the maneuver. Normally, a space system is designed to meet a certain amount of ΔV over its lifetime. Spacecraft mass and propulsion performance play a significant role in ΔV calculations, and this will be shown throughout the paper.

1. JUSTIFICATION FOR SATELLITE REFLUIDING

Fluids are one of the most critical components on any spacecraft. For instance, without fuel the spacecraft cannot reach its orbit or maintain that orbit. Fuel also enables the satellite to maneuver to desired locations. Besides fuel, other fluids are needed for manned missions and experimentation. Although refluiding is not necessary for every space system, replenishing fluids on-orbit enhances spacecraft performance in the following ways.

1.1 Increased Lifespan

Because of the large cost of developing and launching satellites, it would normally be economically beneficial to have as long of a life span as possible. The initial act of successfully launching the satellite involves significant risks and could bring an instant end to an expensive venture. Once the satellite has exited the earth's atmosphere on a successful launch, establishing operational capability is another challenge that must be overcome. If any of the seemingly routine tasks such as deploying any antennas, booms and solar arrays were not done correctly, the whole mission could be destroyed.

Satellite refueling would allow the satellite to perform at its highest potential for as long as possible. A satellite that is designed to be refueled could be sent to space with less initial fuel. This means more weight and volume could be used for other crucial satellite components or redundant systems. This would allow for an extremely durable spacecraft that could have a longer and more versatile lifespan because of satellite refueling.

1.2 Degrading Orbits

Many satellite systems today are taking advantage of the Low Earth Orbit (LEO) for systems such as cellular phones that require timeliness and reduced power. A LEO satellite is confronted with aerodynamic forces that higher altitude satellites escape. In LEO there are trace amounts of atmosphere, and the lower the orbit, the more atmosphere is present. This results in drag forces imposed on the satellite that slow it down and produce a loss of altitude. Information on the amount of orbit decay for a given altitude is shown below in Figure 1.1 [6]. To

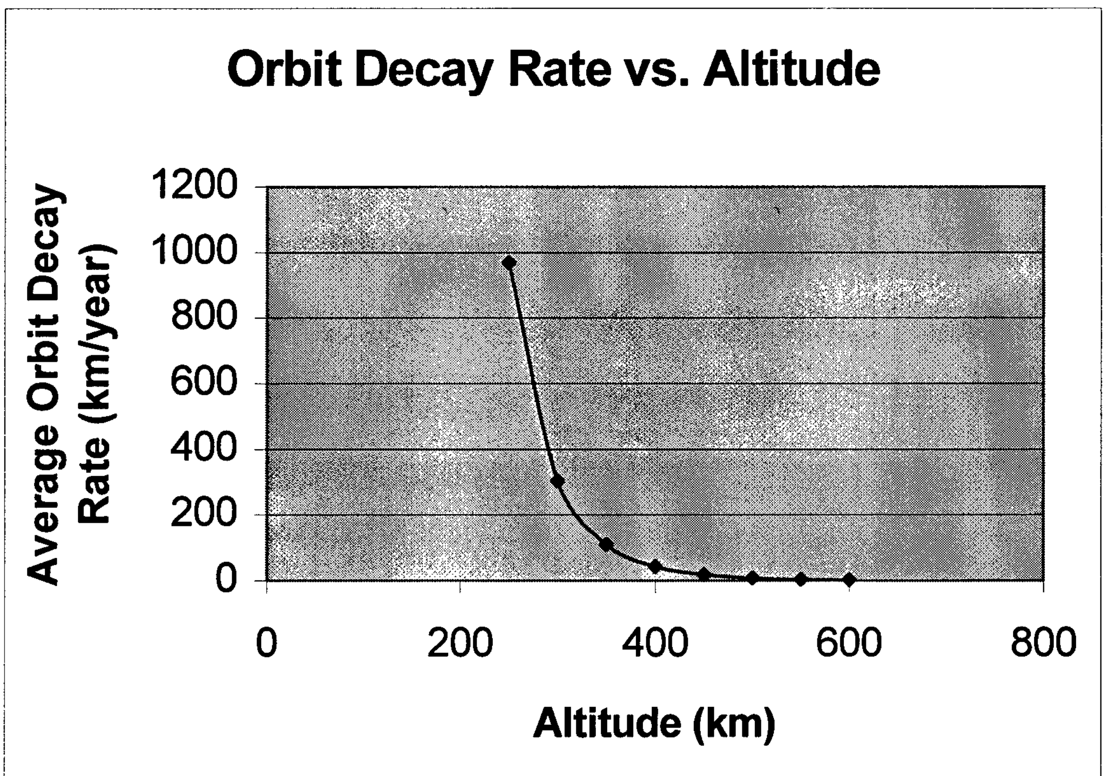


Figure 1.1

To counteract the effects of this altitude loss, the satellite would have to use propellant to achieve the amount of ΔV necessary to keep the desired altitude. This information is presented in Figure 1.2.

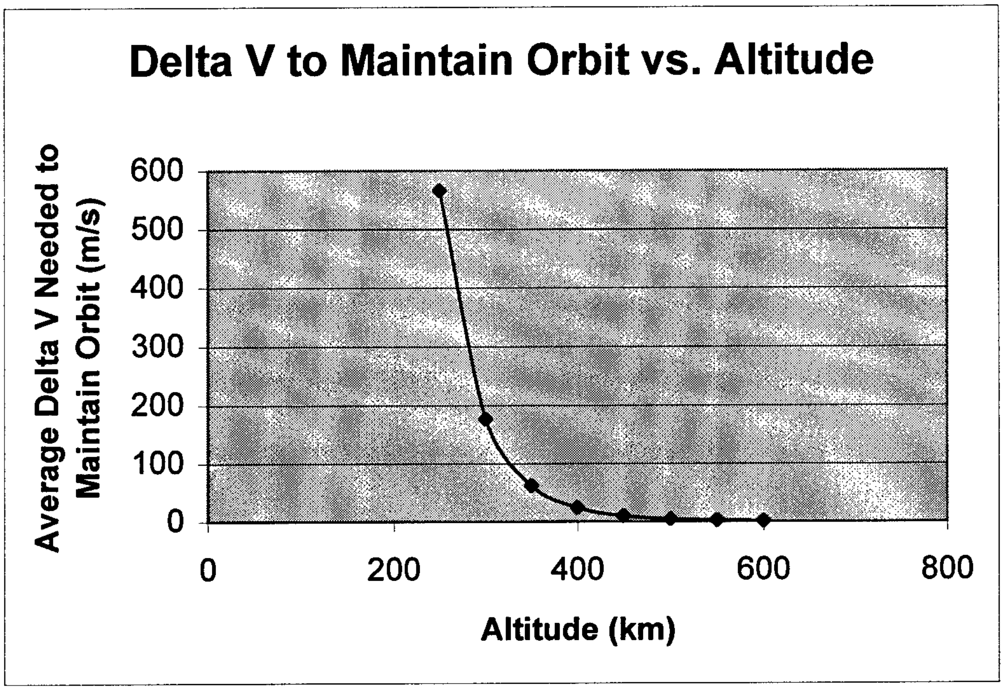


Figure 1.2

Spacecraft in orbits below 400km must perform burns to remain in operation for an extended period of time. Satellite refueling would provide the necessary fuel for these activities.

1.3 Maneuvering

During a satellites operational life, it may have to undergo several position changes to accomplish its mission and nearly every time a satellite changes position, it uses precious fuel.

Today's military uses surveillance satellites to obtain information that can give it the edge in deciding when and where to strike an enemy. Usually, this information is time critical and could be the main factor for a successful mission. If the surveillance satellite was not in the correct position in space to see a desired

ground location, ground operators would either have to wait for it to pass over the spot (a potentially costly option that could be paid in lives) or move the satellite. The more likely option of repositioning the satellite could easily use all the fuel on board making any future maneuvers impossible, hence effectively "killing" the satellite [4]. Satellite refueling would allow the expensive satellite to continue fulfilling its mission.

Constellations of satellites often contain on-orbit spares to replace any individual satellites that become non-operational. If the goal of the constellation were to provide complete global coverage, the on-orbit spare would have to be moved to the vacant position created by the dead satellite. This maneuver could involve a significant amount of fuel depending on the amount of position change needed. If the satellite used all its fuel to accomplish the maneuver, it could not provide any necessary attitude control, stationkeeping, or other maintenance maneuvers. Satellite refueling is a solution to this problem.

1.4 Manned and Interplanetary Missions

Covering great distances in space is somewhat similar to covering great distances on the ground; it takes a lot of fuel. Interplanetary missions (for the sake of argument, we will include the moon) usually make a series of significant burns to get where they are going, and therefore use a lot of fuel. NASA is usually the driving force behind interplanetary missions, and they recognize the need for refueling. In a NASA publication concerning this issue, it was said "Fluid management technologies, including resupply of fluids on-orbit, will be a

key element in future space operations. Systems such as the Space Station Freedom and future Lunar and Mars exploration missions will require periodic resupply of liquids and gases for life support, propellants, reactants, and experiment supplies." [3]. This statement solidifies the importance of a system to transport many different fluids, or "refluiding". Manned missions could possibly be the greatest benefactor from a satellite refluiding system because it would support them in so many ways.

1.5 Other Servicing

It is fairly logical to assume that the servicing vehicle would be built in such a way that it could do more than just refluid. At the least, the servicing vehicle will have some kind of external arm necessary for latch-up with the spacecraft. This arm could be used for many things such as freeing undeployed solar arrays or gravity booms, and possibly replacing used equipment such as batteries. Governments and companies invest large amounts of capital into orbiting assets that often cannot be fixed if problems arise on orbit, and the servicing vehicle could be the solution. The external arm would only add to the enhancements provided by satellite refluiding.

1.6 Conclusion

Satellite refluiding can only improve current spacecraft performance. Although it is not applicable to every space system, it can greatly enhance manned missions and large LEO constellations. In many ways, it can be compared to the way aircraft refueling

increased range and versatility. A satellite refluiding vehicle has the potential to not only replenish fluids, but also service spacecraft in need. The satellite servicer fits right in with the current space concept of doing more with less.

2. FEASIBILITY

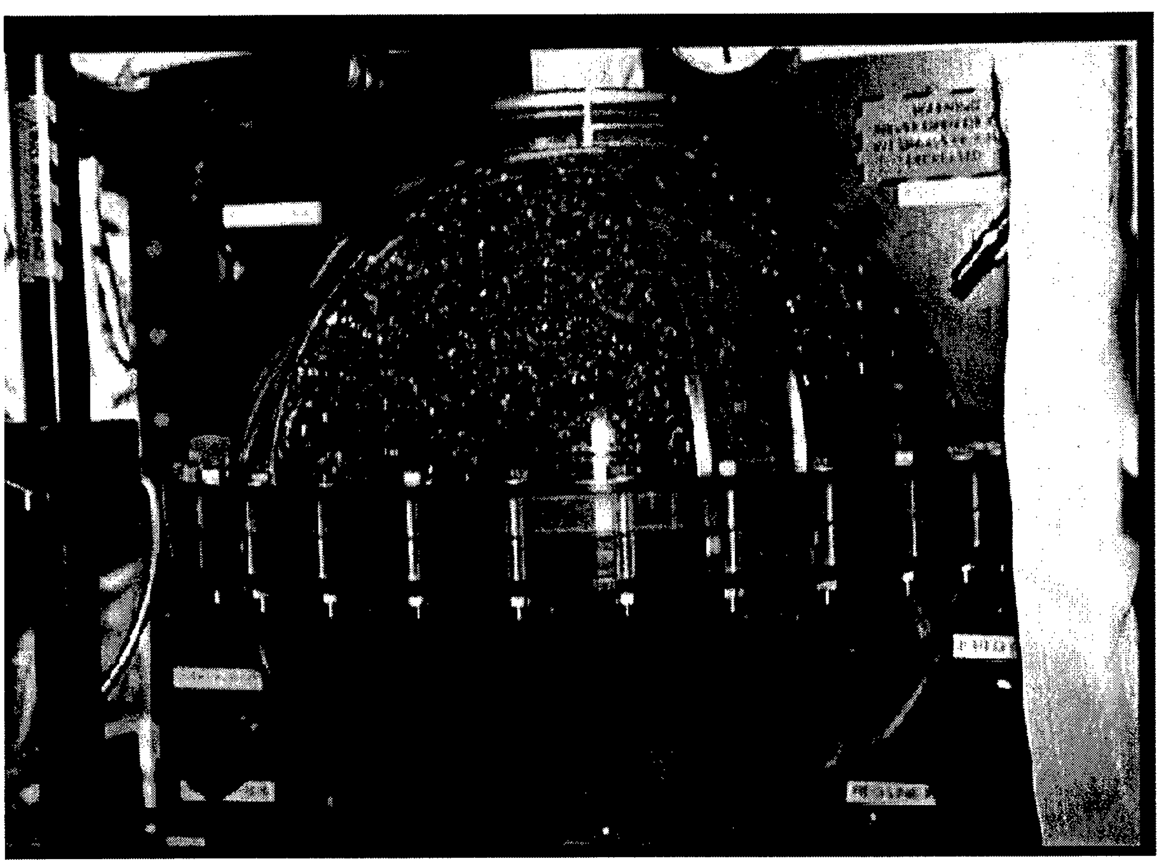
Several ideas have been explored that deal with the resupply of satellite fuels. Because of the zero gravity environment in space, the transfer of fuels has more complex issues than on earth. A satellite cannot simply pull up to a gas station in space and say "fill 'er up". When a fluid is inside a depot tank on-orbit (zero gravity), its location within the tank is always changing. A refluiding system needs to identify the position of fluid and gas within the tank, and then acquire the fluid, before a transfer can be completed. When fluid is added to a satellite, it's entire center of gravity is affected. Any forces that the satellite receives during the refueling process could put it into an undesirable attitude or spin. The transfer of fuels involves venting and vaporization issues that vary for nearly every fluid. A complete understanding of the entire resupply of consumables process is required for successful fluid transfer.

2.1 Experimentation

NASA is extremely interested in the resupply of spacecraft propellants. The engineers at NASA want an understanding of fluid behavior so that future resupplying can be done safely and efficiently. They state that "Simple, proven techniques for transferring a variety of different liquids, from hazardous propellants to cryogens, must be demonstrated" to achieve success in future refluiding attempts [3]. This thinking prompted the execution of experiments on space shuttle missions and at ground-based NASA facilities. The involvement of NASA in refluiding experiments shows a dedication to the topic of satellite refluiding.

2.1.1 STS-53

During this space shuttle flight in late 1992, a series of tests were conducted to "demonstrate techniques for handling liquids in zero gravity for operations such as refueling spacecraft in orbit." [3]. This experiment was titled the Fluid Acquisition and Resupply Experiment or FARE. The space shuttle was equipped with two tanks containing colored water. The astronauts tested drain screen devices that separate gas and gas-free liquid within the tanks because, as it was stated earlier, fluid in low gravity can float around in tanks unpredictably and must be collected before it can be used for refueling. Once the fluid was separated and acquired, the crew transferred the colored water between two clear tanks several times at different pressures and flow rates. One of the tanks is shown below in Figure 2.1 [8,9]. Tests were also performed to investigate propellant slosh characteristics.



2.1.2 STS-57

The second FARE experiment took place with a new fluid-handling device that improves the ability to capture and transfer fluid from a tank. Experiments were also conducted that transfer liquid helium. According to NASA, this Superfluid Helium On-Orbit Transfer (SHOOT) experiment "could increase the lifetime of satellites which require a supply of liquid helium." [8]. Both of these experiments demonstrated the ability to transfer fluids on orbit for the purpose of resupply.

2.1.3 NASA Lewis Research Center

Experiments at the research center have investigated a method for "…refilling cryogenic storage tanks in low gravity" [5]. Two main operational components make up the transfer process; tank chilldown with a controlled venting of vapor, and tank filling without venting. This is called a "no-vent" filling approach and would help minimize required operations on-orbit. Both liquid nitrogen and hydrogen have been tested using large tanks similar to the ones used in space. The researchers have gained knowledge in such subjects as the thermodynamics involved with a cryogenic transfer. More tests of this nature are currently being conducted at the NASA Lewis Research Center to "lead the way in the development of this key, enabling technology" [5].

2.2 Feasibility Assessment

These experiments not only demonstrate that refluiding on orbit is possible, they show that NASA is dedicated to developing this technology. Once a complete understanding is gained through repeated experiments, future space missions will undoubtedly be improved by refluiding.

3. METHODS FOR SATELLITE REFUELING

NASA has proven that fluid transfer in space is very feasible, but they do not have a specific system to implement this technology. Three main ideas for satellite refueling have been, and are being, investigated; direct fluid transfer, tank to vehicle, and propulsion module [2]. A brief description of each method is given below.

Direct Fluid Transfer Direct fluid transfer is very similar to how automobiles are refueled at a service station. Fluid is transferred from a filling tank to the vehicle tank. This technology was demonstrated on space shuttle FARE experiments described earlier in this paper. A common interface between servicing vehicle and spacecraft is desirable so many satellites could be refueled by a single servicer.

Tank-to-Vehicle When the satellite becomes low on fuel (but not completely out of fuel), a servicing spacecraft would be sent out to rendezvous. The servicer would remove the entire empty propellant tank(s) and replace it/them with new one(s). All replacement propellant tanks, also called Orbital Replacement Units (ORUs), would have to be designed in such a manner that the servicing vehicle could safely and efficiently handle them. Both the satellite being refueled

and the ORU must have all necessary mechanical and electrical connections.

Propulsion Module This method goes one step further than Tank-to-Vehicle Assembly, and replaces the entire propulsion system. Once again, the entire propulsion system would be an ORU and must have the necessary features that allow for safe and efficient replacement. The Propulsion Module would consist of an entire system that includes tanks, lines, main engines, thrusters, and propellant management systems.

Each of these methods would require different connections for the interface between servicer and satellite. A description of the number of interfaces is given below in Table 3.1.

	Direct Fluid Transfer	Tank-to-Vehicle	Propulsion Module
Interfaces	1. Docking 2. Fluid Transfer	1. Docking 2. ORU interfaces - Fluid - Electrical - Mechanical 3. Interstorage	1. Docking 2. Module Interface 3. Interstorage

Table 3.1

These interfaces are somewhat self-explanatory, except for "interstorage" which

is necessary on the Tank-to-Vehicle and Propulsion Module for holding the empty component while the new one is transferred from the servicer and installed. As the number of interfaces increases, so does the system complexity. This is just one of the factors that are used when comparing these methods.

Each of these three systems has its own unique advantages and disadvantages. A comparison is illustrated below in Table 3.2.

	Direct Fluid Transfer	Tank-to-Vehicle Assembly	Propulsion Module Exchange
Advantages	-Has the least impact on vehicle design -Allows for the most utilization of fuel (less wasted fuel) -Requires the least amount of interfaces (2, 1 for docking and 1 for fluid exchange)	-Requires small operations time -The tanks could be reused	-Same as Tank-to-Vehicle Assembly
Disadvantages	-Requires a considerable amount of time for refueling -The transfer of propellants from tanks raises safety concerns -Requires pumps and propellant acquisition devices	-Tanks are exchanged before they are completely empty, which wastes fuel -Servicing vehicles have to carry the fuel *and* the tanks to the satellite (more weight and space) -Limits the design of both the satellite and the servicing vehicle -Large shift in center of gravity between exchanges	-Has the same disadvantages as the Tank-to-Vehicle Assembly, but on an even larger scale

Table 3.2

3.1 Analysis of Refluiding Methods

If we are comparing all 3 methods, the problems associated with Tank-to-Vehicle Assembly and Propulsion Module Exchange lead us to believe that these two options are far too problematic. Both of these choices require adding not only the necessary fuel to the satellite, but also significant amounts of structure (at the least, propellant tanks). Also, these two options require a dedicated system on the servicer that would need to remove and replace the orbital replacement units (ORUs). This servicing system would undoubtedly need several robotic or astronaut controlled arms with varying degrees of freedom to accomplish the exchange. These arms would add more mass, volume, and complexity problems to the already difficult tank-to-vehicles and propulsion module concepts.

The Direct Fluid Transfer is currently the option with the most benefits and fewest downfalls. It only needs to transport fuel to the satellite and the satellite can use all fuel that is transferred. This system also requires a less complex system for latch-up with the satellite being refueled. The "reusability" of direct fluid transfer is the best among the three available choices; the servicer could be refilled each time a spacecraft needed refluiding, and could possibly be used for several different types of fluid. At this time, Direct Fluid Transfer is the most attractive method for refueling satellites.

3.2 Satellite Refluiding Vehicles

In order to transport fluid to a spacecraft in need, either a manned or automated

servicer must be utilized. The following descriptions and analysis of each option give a preliminary understanding of the two systems.

3.2.1 Manned Refluiding

As the name implies, this option would utilize an astronaut to help accomplish its mission. In 1993, the University of Maryland did an extensive project dealing with the use of a Manned On-Orbit Servicing Equipment (MOOSE) [1]. I will use this design to demonstrate some of the characteristics a manned servicer would include.

The MOOSE was designed to be based at the International Space Station Freedom and deployed to service space assets as far out as a 3-day round-trip to Geosynchronous orbit (GEO). The system is designed to service up to 3 satellites in one mission to reduce overall costs. The astronaut would live in the MOOSE and perform all refueling and servicing tasks from within the spacecraft. The astronaut would control a seven degree of freedom (DOF) Telerobotic Manipulator Arm, a four DOF Telerobotic Grappling Arm, and a Manual Manipulation System. The MOOSE propulsion system consists of a liquid oxygen and liquid hydrogen (LOX/LH2) main propulsion unit, a Helium-pressurized Hydrazine system for smaller maneuvers, and a Helium cold gas thruster network for proximity operations. The propulsion system will be described in more detail shortly, and will be the focus of my analysis. A complete system for astronaut support was also designed, and the mass of this, and other space systems, can be shown below as it was published.

MASS BREAKDOWN

Component	Mass (kg)
Structure	200
Cabin	355
Cabin Systems	663
Aerobrake	650
Tankage	610
Power	52
Avionics	196
Propulsion	300
ACS	41
LOX	1334
LH2	9335
Hydrazine	522
Helium	223
Crew	90
Payload	500
Dry Mass	3067
Flight Mass	15071

As you can see from the above list, the manned mission drives much of the mass requirements. The 365kg set aside for cabin mass and the 663kg for cabin systems are examples of the mass needed for such things as food, exercise area, sleep, and waste disposal. Only 500kg are allocated for payload, which would be propellant for a satellite fueling mission.

If we look closer at the mass breakdown, we can see that the dry mass is made up of the following components.

Dry Mass Breakdown

Component	Mass (kg)
Structure	200
Cabin	355
Cabin Systems	663
Aerobrake	650

Tankage	610
Power	52
Avionics	196
Propulsion	300
ACS	41
Dry Mass	3067

This published value could technically be called the dry mass, but it could not be used in propulsion calculations because it excludes more than just fuel, as shown below.

Flight Mass Breakdown

Component	Mass (kg)
LOX	1334
LH2	9335
Hydrazine	522
Helium	223
Crew	90
Payload	500
+ "Dry" Mass	3067
"Flight" Mass	15071

It would seem that the proper "dry mass" would include at least the crew and portion of the Helium used for pressurant. During the ΔV calculations described in the upcoming portion of this paper, we will see why this is important.

3.2.1.1 Main Propulsion System

As mentioned earlier, a liquid oxygen and liquid hydrogen (LOX/LH2) bipropellant system will be used for the main engines. This system provides very

high performance for a chemical rocket engine, with a vacuum potential ISP of 450 seconds. The system performs only three large burns:

1. GEO Transfer Injection
2. GEO Circularization
3. LEO Transfer Inject

Normally, a large fourth burn for LEO circularization would be needed, however the designers are incorporating a reusable aerobrake to slow the MOOSE down upon it's return to the space station. The aerobrake uses the drag forces implied by the small amounts of atmosphere in LEO.

A helium-pressurized Hydrazine monopropellant system will be used with the attitude control system and for small maneuvers such as mid-course corrections. Extremely delicate maneuvers will be conducted with 40 Helium cold-gas thrusters. An upcoming description of the ΔV will show how these systems are used during the servicing mission

3.2.1.2 ΔV

The published ΔV budget for MOOSE is listed below.

ΔV BUDGET for GEO MISSION

Event	ΔV (m/s)
Separate	3
GEO Transfer Inject	2400
Midcourse	15
Geo Circularization	1762
Orbit Trim	9
GEO Operations	208
LEO Transfer Inject	1844
Midcourse	20
Aeromanuever	67

LEO Circularization	122
Rendezvous & Docking	18
Reserves	532
TOTAL	7000

Once again, it is important to mention that normally the ΔV associated with LEO Circularization would have been significantly higher (in the neighborhood of 2000m/s), but the design group cleverly incorporated an aerobrake to slow the vehicle down upon re-entry into LEO. While this is a good idea that saves propellant and can be reused, the designers have flaws in other ΔV areas.

3.2.1.3 MOOSE Propulsion Analysis

While investigating the MOOSE propulsion system, I found a problem with ΔV that I believe the designers overlooked. In the mass breakdown listed earlier (pages 21-22), the published values for dry mass and flight mass were shown as:

"Dry" Mass	3067
"Flight" Mass	15071

I believe the designers used these values for their ΔV calculations, as shown below in Table 3.3.

Activity	DELTA V (m/s)	Initial Mass (kg)	Final Mass (kg)	Propellant Mass Used (kg)	Propellant	ISP (sec)
Separate	3	**15071**	15045.27411	25.72588855	COLD gas	179
GEO Transfer Inject	2400	15045.2741	8735.550519	6309.723593	Main	450
Midcourse	15	8735.55052	8680.0728	55.47771887	Hydrazine	240
GEO Circularization	1762	8680.0728	5823.437308	2856.635492	Main	450
Orbit Trim	9	5823.43731	5801.218954	22.21835405	Hydrazine	240
GEO Operations	208	5801.21895	5310.695619	490.5233347	Hydrazine	240
****Remove 500kg for payload						
LEO Transfer Inject	1844	4810.69562	3168.085038	1642.610582	Main	450
Midcourse	20	3168.08504	3141.286981	26.79805673	Hydrazine	240
Aeromaneuver	67	3168.08504	3079.200416	88.88462176	Hydrazine	240
LEO Circularization	122	3141.28698	3055.662363	85.62461804	Main	450
Rendezvous & Docking	18	3079.20042	**3047.797899**	31.4025168	COLD gas	179

Table 3.3

As you can see from Table 3.3, the MOOSE can return to the space station with a mass of approximately 3047.8kg. This calculated value is comparable to the 3067 kg "dry mass" that we have been discussing. However, it must be said again that this "dry mass" value does not include the crew mass or the Helium used for pressurant in the Hydrazine system. This seems to be an error in the design. Furthermore, Table 3.3 also does not include the ΔV margin of 532 m/s, which would only require more fuel. A manned mission requires that safety be a prime concern, and the current MOOSE design simply does not have the propulsion performance needed to return the astronaut and servicer safely.

To make matters worse, the designers of the MOOSE also assumed that the space station Freedom would be positioned at 333km x 444km elliptic orbit with an inclination of 28.5°. We now know that the space station orbit is going to be nearly circular at 370km altitude and highly inclined at 51.6°, which would

greatly effect the amount of ΔV needed. Table 3.4 shows the difference in the amount of ΔV needed just for the flight out to GEO using the 10% perigee-90% apogee rule for plane change calculations.

Initial Altitude (km)	Final Altitude (km)	Initial Inclination (Deg)	Final Inclination (Deg)	ΔV GEO trans inj (km/s)	ΔV GEO Circ. (km/s)
370	35786	28.5	0	2.43061805	1.765778876
370	35786	51.6	0	2.486017265	2.285142356
			DIFFERENCE	0.055399215	0.53813166
			TOTAL	**0.593530875 (km/s)**	

Table 3.4

The additional 593.5 m/s needed just for getting to GEO exceeds the reserves incorporated in the MOOSE, therefore requiring a redesign of the MOOSE propellant budget. The return trip from GEO would only add to the ΔV problems associated with a space station orbit of 51.6°. Table 3.5 shows the difference in ΔV for LEO transfer injection. The LEO circularization calculation is omitted because of the aerobrake.

Initial Altitude (km)	Final Altitude (km)	Initial Inclination (Deg)	Final Inclination (Deg)	DELTA V LEO trans inj (km/s)
35786	370	0	28.5	1.763267967
35786	370	0	51.6	2.284295987
			TOTAL	**0.52102802 (km/s)**

Table 3.5

If we add this amount of ΔV to the GEO transfer requirements, a total of 1.1145km/s of ΔV is needed for the space station inclination of 51.6°. In order to meet the demands of this additional ΔV, the MOOSE propulsion system would need significant redesign.

3.2.1.4 MOOSE Conclusion

As it was said, the MOOSE was only a design concept that I used for demonstration purposes. However, the results of the MOOSE propulsion analysis show what I believe to be a recurring problem. The mass requirements for a manned mission raise the inert mass to levels that make it difficult to perform a GEO mission using even the highest performance chemical rocket engines. The available options are to lower the vehicle mass, add more fuel, or implement a higher performance propulsion system. Lowering the vehicle mass would be difficult to do and would only remove small amounts of inert mass. The option of adding more fuel would eventually reach a point where the system would simply be too big. As for higher performance propulsion, an electric or nuclear system are really the only available options. While these two systems are not widely proven in space today, there may be a time in the near future where they will be feasible. Overall, a manned servicer cannot be implemented unless higher technology is used.

3.2.2 Automated Refluiding

An automated refueler would face many of the same challenges of the manned

method, without the necessary human support requirements. Because a crew cabin and support system would not be necessary, the servicer could be built smaller and more robust, that is, more mass could be incorporated toward mission essential components such as propulsion, external control arms, latch-up mechanisms, and pumps. The non-manned servicer could either be completely automated or partially human controlled, and for the scope of this paper we will assume that either is possible. In order to demonstrate how a propulsion system for an automated servicer would perform, I will once again return to the MOOSE example. To avoid confusion, I will remove the letter M from MOOSE because we are no longer talking about a manned servicer. The term OOSE will be used during this section to describe the on-orbit servicing equipment.

The OOSE design would have the following mass breakdown if the components that are solely needed for a manned mission were deleted:

MASS BREAKDOWN

Component	Mass (kg)
Structure	200
Cabin	0*
Cabin Systems	0*
Aerobrake	650
Tankage	610
Power	52
Avionics	196
Propulsion	300
ACS	41
LOX	1334
LH2	9335
Hydrazine	522
Helium	223
Crew	0*
Payload	500
Flight Mass	13963

From this mass breakdown, an actual "dry mass" can be calculated. It was assumed that 50 kg of Helium was used as pressurant and therefore would be included in the "dry mass".

DRY MASS BREAKDOWN

Component	Mass (kg)
Structure	200
Aerobrake	650
Tankage	610
Power	52
Avionics	196
Propulsion	300
ACS	41
Helium	50
Dry Mass	2099

Because we are assuming that the same amount of fuel is used as with the manned mission, and we have significantly less inert mass, much higher performance can be obtained. However, this higher performance will be necessary because for the analysis of the automated system the higher ΔV requirements of the 51.6° inclination will be used.

3.2.2.1 Automated System Propulsion Analysis

Table 3.6 shows how the propulsion system on OOSE would perform. The necessary ΔV for the 51.6° plane change is incorporated into the GEO Transfer Inject, GEO Circularization, and LEO Transfer Inject calculations. It

was assumed that the aerobrake could perform in a similar manner for the LEO circularization.

Activity	DELTA V (m/s)	Initial Mass (kg)	Final Mass (kg)	Propellant Mass used (kg)	Propellant	ISP (sec)
Separate	3	**13963**	13939.16544	23.83455522	COLD gas	179
GEO Transfer Inject	2486	13939.1654	7937.182127	6001.983318	Main	450
Midcourse	15	7937.18213	7886.774685	50.40744229	Hydrazine	240
GEO Circularization	2314	7886.77468	4669.283151	3217.491534	Main	450
Orbit Trim	9	4669.28315	4651.468279	17.81487131	Hydrazine	240
GEO Operations	208	4651.46828	4258.162364	393.3059155	Hydrazine	240
		****Remove 500kg for payload				
LEO Transfer Inject	2285	3758.16236	2239.645644	1518.51672	Main	450
Midcourse	20	2239.64564	2220.701029	18.9446149	Hydrazine	240
Aeromaneuver	67	2239.64564	2176.80956	62.83608349	Hydrazine	240
LEO Circularization	122	2220.70103	2160.169572	60.53145686	Main	450
Rendezvous & Docking	18	2176.80956	**2154.609869**	22.19969133	COLD gas	179

Table 3.6

Table 3.6 shows that the OOSE can return to the space station from GEO having a mass of 2154.6 kg. This value is greater than the calculated 2099kg showing that the automated system can accomplish the mission with mass to spare.

Table 3.7 below shows the amount of each fuel that is necessary for the automated system to accomplish the mission. As you can see, these calculated values are nearly identical to the published numbers demonstrating again that the automated system is viable.

Mass Summary (kg)			
	Calculated	Published Numbers	Difference
LOX	1352.25493	1334	18.25493
LH2	9465.784509	9335	130.78451
Hydrazine	539.3523519	522	17.352352
Helium	45.86955004	223	-177.13045
		TOTAL	-10.73866

Table 3.7

There is a very small amount of propellant mass left over that could be used for reserves. Although these calculations show that the automated system is possible, it accomplishes the mission with very little room for error.

3.2.2.2 Automated System Conclusion

The OOSE example used in this section fairly accurately predicts the performance of an automated servicer propulsion system. The results show that it is possible to leave from the space station, service a satellite in GEO, and return to the station. However, the OOSE propulsion system used the highest performance chemical engine available and accomplished the mission with very little excess propellant. It would seem logical that a mission such as servicing satellites in GEO, which would require a large amount of resources, should have a propulsion system that can greater exceed it's demands.

4. Recommendation and Conclusion

Satellite refluiding is a technology that is feasible and can only enhance space assets, but how to implement this technology with a servicing vehicle remains a difficult problem. The MOOSE example demonstrates that a manned serving vehicle would be an incredibly difficult system to develop. It was shown that the MOOSE design, as it currently stands, does not have the ability to fulfill its mission of being based at the space station and serving satellites in GEO. The system was already using the highest performance chemical rocket engine available, and although it could be redesigned with larger propellant tanks, there would eventually be a size limit. A manned mission would need more performance than the MOOSE could provide.

The automated system example shows it is feasible to be based at the space station and service satellites in GEO. Because the automated system does not have the necessary mass needed for life support, performance can be enhanced. However, the automated system accomplished the GEO mission with only a very small margin. Once again, this system used the highest performance chemical rocket engine available and still could not service more than one satellite in GEO. A higher performance propulsion system, such as nuclear or electric, is needed even in an automated servicer. I believe that a time consuming and capital rich venture, such as creating a servicing vehicle, should be based on a system that can greatly exceed the minimum performance necessary.

In conclusion, I would like to add some satellite refluiding ideas for the future. The demand for satellite servicing has been demonstrated, and the technology is in place to make it possible. The number of space assets continues to grow, only increasing the

demand for a servicing spacecraft. At the time of the completion of this paper, the U.S. Air Force had just contracted to BOEING for the construction of a solar powered, electronic propulsion, orbital transfer vehicle [7]. Although the specifics of this project are not published (read: classified), I believe that this is the type of technology necessary for a servicing vehicle. The solar powered, electronic propulsion system opens up a new world of performance and reusability. A system, such as this, could be used by a commercial company that contracted for satellite servicing and refluiding. As with any developing technology, once the building blocks of demand and feasibility are in place, the potential for profit is not far behind.

References

1. Budinoff, J., et al. MOOSE: Manned On-Orbit Servicing Equipment, NASA-CR-197151, 1993

2. Clarke, Margaret M., et al. Robotic On-Orbit Fueling of SEI Vehicles, Engineering, Construction, and Operations in Space III: Space '92, 1992

3. Dominick, Sam M. and Driscoll, Susan L., Fluid Acquisition and Resupply Experiment (FARE-I) Flight Results, AIAA/SAE/ASME/ASFE 29th Joint Propulsion Conference and Exhibit, 1993

4. Ridolfi, Capt. Don, Satellite Refueling: The Tactical Advantage, SWC Space Tactics Bulletin, Winter 1995

5. Taylor, William J. and Chato, David J., Comparing the Results of an Analytical Model of the No-Vent Fill Process With No-Vent Fill Test Results for a 4.96m^3 Tank, AIAA/SAE/ASME/ASFE 28th Joint Propulsion Conference and Exhibit, 1992

6. Wertz, James R. and Larson, Wiley J., Space Mission Analysis and Design, Kluwer Publishing, 1991

7. Air Force Times, 7 April 1998

8. www.spacelink.nasa.gov/NASA.Projects/Human.Exploration.and.Development.of.Space/Human.Space.Flight/Shuttle/Shuttle.Missions/Flight.052.STS-53/

9. www.spacelink.nasa.gov/NASA.Projects/Human.Exploration.and.Development.of.Space/Human.Space.Flight/Shuttle/Shuttle.Missions/Flight.056.STS-57/